NSWCDD/TR-92/124

AN EXPLOSIVELY ACTUATED ELECTRICAL SWITCH USING KAPTON INSULATION

BY DOUGLAS G. TASKER, RICHARD J. LEE, and PAUL K. GUSTAVSON

WEAPONS RESEARCH AND TECHNOLOGY DEPARTMENT

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NAVAL SURFACE WARFARE CENTER

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FOREWORD

The designs and manufacture of explosively actuated electrical closing switches are described. The switches are fast operating; can handle high electrical power; are energy efficient, with low inductance and resistance when closed; but they are able to withstand high voltages when open. The switches exploit shock-induced conductivity effects in Kapton, a polypyromellitimide insulator manufactured by DuPont.

The key to the successful operation of these switches is to use them in the transverse mode of operation, i.e., where the detonation wave travels transverse to the applied electric field. A series of experiments are described in which the parameters of switch design that are crucial to its successful operation have been identified. Other experiments demonstrate that conduction in the shocked Kapton is caused by shock-induced conduction, and not by mechanical tearing of the polymer. The results of using the switches in various applications are given.

This work was funded by the Office of Naval Technology as part of the NSWCDD Explosives and Undersea Warheads Block Program.

The authors wish to acknowledge the significant contribution of Mr. James Goforth of the Los Alamos National Laboratory, Code M-6, who first suggested the use of Kapton in the Electromagnetic Energy Enhancement application. We would also like to thank our colleagues who made valuable contributions to the experimental effort: Robert Hay, Nathaniel Snowden, and Bernard Snowden. The authors are grateful to J. Forbes who made many valuable comments on this manuscript.

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ABSTRACT

The designs and manufacture of several explosively-actuated, electrical closing switches are described. The switches are fast operating; can handle very high electrical power; are highly energy efficient, with low inductance, and low resistance, when closed; but are able to withstand very high voltages when open. The switches exploit shock-induced conductivity effects in Kapton, a polypyromellitimide insulator. The key to the successful operation of the switches is to use them in the transverse mode of operation, i.e., where the detonation wave travels transverse to the applied electric field. Through the research described in this report, the many factors that are crucial to the design of an effective switch have been identified. The results of using the switches in numerous applications are provided.

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CHAPTER 1

INTRODUCTION

Ongoing research at the Naval Surface Warfare Center Dahlgren Division White Oak Detachment (NSWCDDWODET) has been concerned with the properties of detonating explosives during Electromagnetic Energy Enhancement (EEE).[1] EEE is the process by which the performance of explosives are enhanced by the addition of electrical energy in the reaction zone of the explosive. With EEE the explosives are subjected to very high electric fields, typically approaching 2×10^7 V/m. Unless special precautions are taken the explosive may break down in this field at the site of a flaw or imperfection; this would direct energy away from the reaction zone with a resultant degradation of performance. These problems were overcome using Kapton to insulate the explosive. When the explosive was detonated the Kapton was 'shocked-up' into its conducting state which allowed current to flow through the explosive with negligible resistance. The use of Kapton was suggested by Mr. James Goforth of Los Alamos National Laboratory (Code M-6). We have used this technique successfully, since April 1984, in a variety of experimental configurations. In April 1989, it was decided to study the conduction properties of the Kapton in more detail, and to exploit them in the design of a simple explosively-actuated closing switch.

It has been known for some time that various insulating polymers become good electrical conductors when mechanically shocked to very high pressures, i.e., above 10 GPa.[2-10] Various researchers have attempted, unsuccessfully, to exploit this shock-induced electrical conductivity for explosively-actuated electrical switches,[11] and one researcher has claimed that shock-induced electrical conduction in Kapton (polypyromellitimide) does not occur.[12] The devices that have been attempted prior to our work are typified by a detonating explosive propagating a shock wave into the polymer in a direction parallel to the applied electric field; see Figure 1-1(A). The disadvantage of this technique is that the shock duration is short, i.e., less than 1 μs, so the switch does not conduct electrical current long enough to be useful.

As part of our studies of the electrical conducting properties of high explosives and EEE we found that the polymers can be made to conduct very effectively with a transverse (sweeping) detonation wave. With our method the detonation propagates a shock wave perpendicular to the direction of the electric field; see Figure 1-1(B).

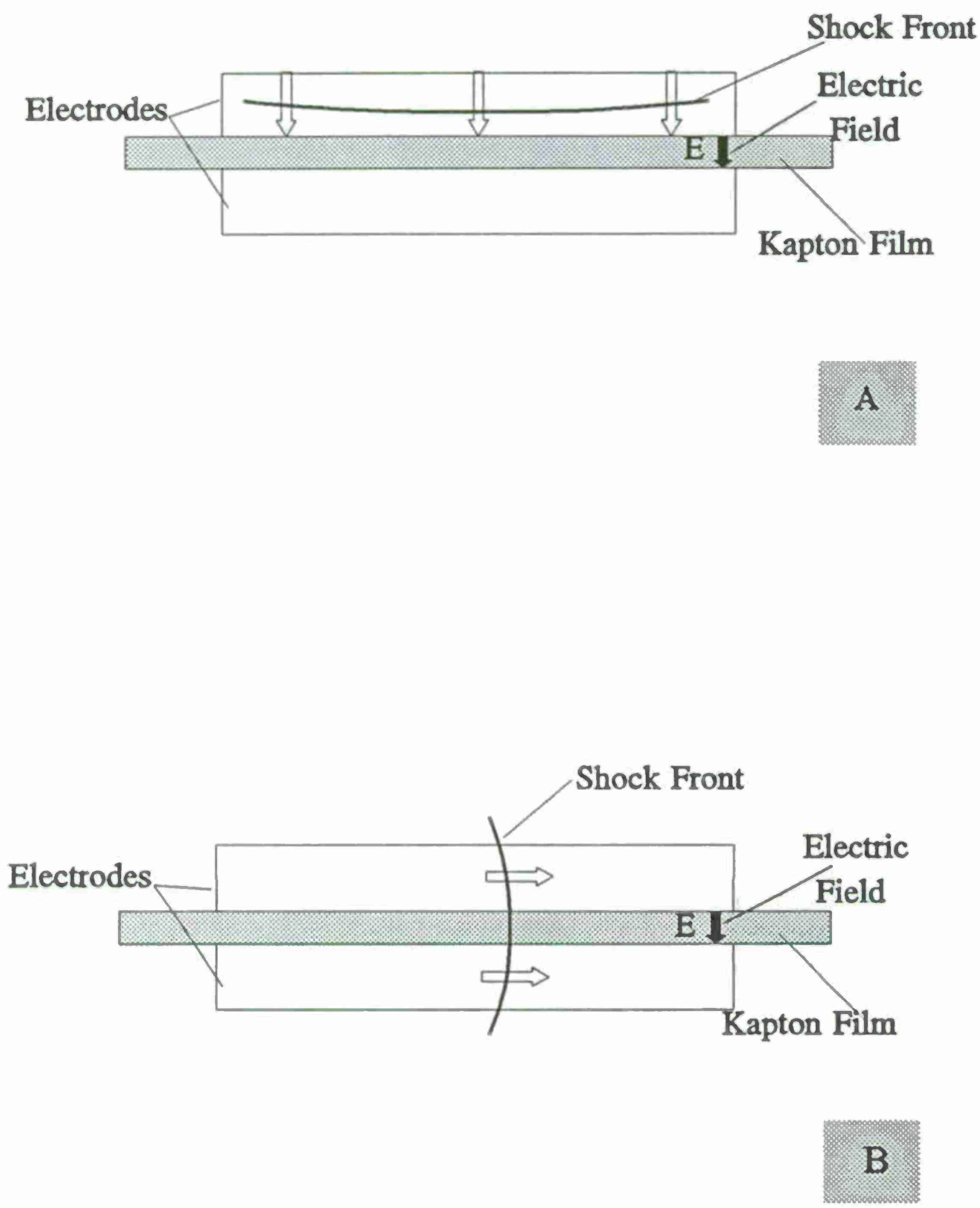

FIGURE 1-1. DETONATING EXPLOSIVE PROPAGATES SHOCK WAVE: (A) PARALLEL TO, (B) TRANSVERSE TO ELECTRIC FIELD

With the transverse (sweeping) wave technique, electrical conduction is maintained in the switch for as long as the detonation wave can be sustained between the electrodes, e.g., tens or hundreds of microseconds.

In the course of developing the closing switch technique, the parameters in the switch design crucial to its successful operation have been determined. In particular, we have studied the effects of adhesive layers, electrode thickness, insulating polymer thickness, and explosive electrical conductivity on the efficiency of the switch. This work is described in Chapter 2.

One dimensional, plane wave experiments have also been performed to observe the mechanisms of shock-induced conduction in Kapton films. It is concluded that conduction occurs as soon as a shock wave has crossed the full thickness of the film, i.e., within 10 ns of shock arrival at the face of the Kapton. Consequently, conduction is due to shock-induced conductivity and not mechanical rupture of the film.

The results of the experimental studies have been applied to the design of various switches which are described in Chapter 3. The results of using these different switches in numerous applications are provided in Chapter 4.

CHAPTER 2

EXPERIMENTAL STUDIES

TRANSVERSE WAVE EXPERIMENTS

To measure the electrical resistance of explosive sheets and of Kapton, the transverse wave experiment was developed. The experiment is illustrated in Figure 2-1 (not to scale). The term 'transverse' refers to the fact that the detonation velocity vector is normal or transverse to the applied electric field.

At the beginning of the experiment a voltage of up to 5 kV was applied between the 125 μm thick copper foil electrode and the 12.7 mm thick brass electrode. Both conductors were 12.7 mm wide (into the paper as drawn). On the left of the assembly, the copper foil was in direct contact with the 3 mm thick, 75 mm wide explosive sheet. From right to left, i.e., the direction of detonation, the explosive was 230 mm long. On the right of the apparatus, a sheet of Kapton of at least 25.4 mm width was sandwiched between the copper electrode and the explosive. The nature of the Kapton film was varied from experiment to experiment, i.e., its thickness, and adhesive layer (or its absence) was changed.

A second sheet of Kapton was placed on the top of the copper foil on the left as a spacer. The whole assembly was lightly compressed by clamps which were insulated with 3.175 mm thick polyethylene sheets. The use of slight compression and the Kapton spacer forced the copper foil to bend as shown in Figure 2-1, thereby minimizing any air gaps.

The explosive was initiated by a line wave generator and the detonation travelled along the explosive from left to right. The electrodes were connected to the power supply on the right side of the assembly, i.e., furthest away from the line wave generator.

The arrangement of copper foil and Kapton was designed so that on the left of the experiment (the beginning) the two electrodes were placed directly against the explosive and measured only the resistance of the explosive; on the right both the Kapton and explosive were between the electrodes and therefore, the total resistance of Kapton and explosive was measured. Consequently, in the one experiment the individual resistances of the explosive and the Kapton could be found.

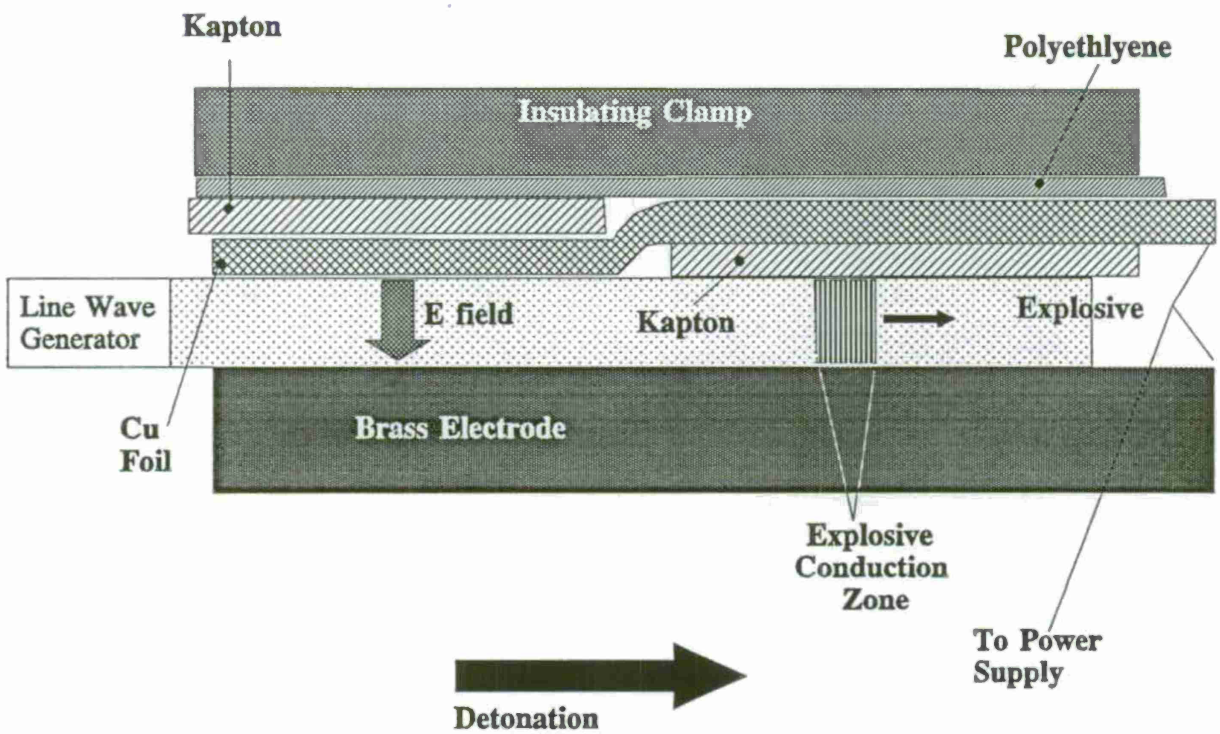

FIGURE 2-1. TRANSVERSE WAVE EXPERIMENT

BASIC CIRCUIT

The fundamental electrical circuit of all the resistance measurement experiments is shown in Figure 2-2. The main circuit comprised of a capacitor, C; an electrical closing switch, S; a transmission line inductance and resistance, L_s and r; and the explosive load inductance and its resistance, L_x and R_x. In the experiments described here the resistance R_x may also include the resistance of the shocked Kapton insulation. The capacitor C represents the power source; this was a 50 μF high voltage capacitor connected by a transmission line with an inductance of $L_s = 2\ \mu$H and a resistance of $r = 0.1\ \Omega$. The transmission line was designed to minimize inductance, it was manufactured from four Reynolds type C coaxial cables in parallel. Electrical diagnostics were used to measure the current, i; the rate of change of current, di/dt; and the voltage, V_x. To eliminate contact resistance errors, the voltage was measured using a four-probe technique.[13]

The initial voltage on the capacitor C in these experiments was typically 5 kV. There are several advantages to using such high voltages. First, the contact potentials that exist between the various conducting materials (explosives, metals, and Kapton), which are typically only a few volts, are too small to affect the high voltage measurements. Second, the large currents that are obtained are well-suited to high speed, high linearity current measurements using Rogowski coils or current transformers (shown in Figure 2-2).

The capacitor, the transmission line, and the explosive load form a classic LCR series resonance circuit. When the switch is closed the circuit will resonate if it is not sufficiently damped or dissipative. The state of damping is expressed by the quality factor, q. If Z_0 is the pulse impedance then from classical circuit theory:

$$Z_0 = \sqrt{\frac{L_s + L_x}{C}}, \qquad q = \frac{Z_0}{r + R_x} \tag{2-1}$$

For simplicity we replace the total inductance with L, and the total resistance with R, then

$$R = r + R_x, \quad L = L_s + L_x \tag{2-2}$$

Using conventional circuit theory we equate the sum of the voltages in the circuit to the voltage on the capacitor, V_c. In this analysis the impedance of the voltage probe, R_v, is considered too large to affect the circuit. If time t = 0 represents the time when the switch is closed we have

$$\frac{1}{C}\int_0^t i\,dt + L\frac{di}{dt} + iR = V_c \tag{2-3}$$

The classic solution to this series LCR circuit can be expressed as

$$i(t) = \frac{V_c}{Z_0'} \sin(\omega_0' t)\, e^{\frac{-R}{2L}t} \tag{2-4}$$

$$\text{where} \quad \omega_0' = \omega_0 \sqrt{1 - \frac{1}{4q^2}}\,,$$

$$\omega_0 = \frac{1}{\sqrt{LC}}, \quad q = \frac{\omega_0 L}{r}, \tag{2-5}$$

$$Z_0 = \sqrt{\frac{L}{C}} = \omega_0 L, \quad \text{and} \quad Z_0' = \omega_0' L.$$

Now the voltage across the unknown resistance is iR_x so

$$iR_x = \frac{V_c R_x}{Z_0'} \sin(\omega_0' t)\, e^{-\frac{R}{2L}t} \tag{2-6}$$

In these experiments the inductance L_x was typically less than 1 nH. Small corrections were made for the voltage across L_x by measuring L_x prior to the experiment, and subtracting L_x di/dt from the measured voltage, V_x.

VOLTAGE MEASUREMENTS

It is difficult to measure voltage accurately in explosive experiments because of the rapid changes of current, i.e., di/dt $\geq 10^{10}$ A/s. These errors and their elimination are addressed elsewhere.[13] The rapid changes are due to the short time durations of the experiments. Consequently, the stray inductances in both the explosive circuits and the voltage probes can cause large errors in voltage measurement. As discussed in Reference 13, large voltage errors can be caused by the mutual inductances between the explosive's circuit and the voltage probes. These errors are minimized by careful design including the use of parallel striplines; in this work mutual inductances have been reduced to less than 1 nH, so that the voltage errors were negligible.

Commercial oscilloscope voltage probes are unsuitable for this work; they are poorly screened from magnetic disturbances and exhibit large voltage errors due to the mutual inductance between the main circuit and the voltage probe circuit. Moreover, the direct connection of the ground wire of a voltage probe invariably produces large voltage errors due to ground loop effects. In this work ground loops are eliminated by using current

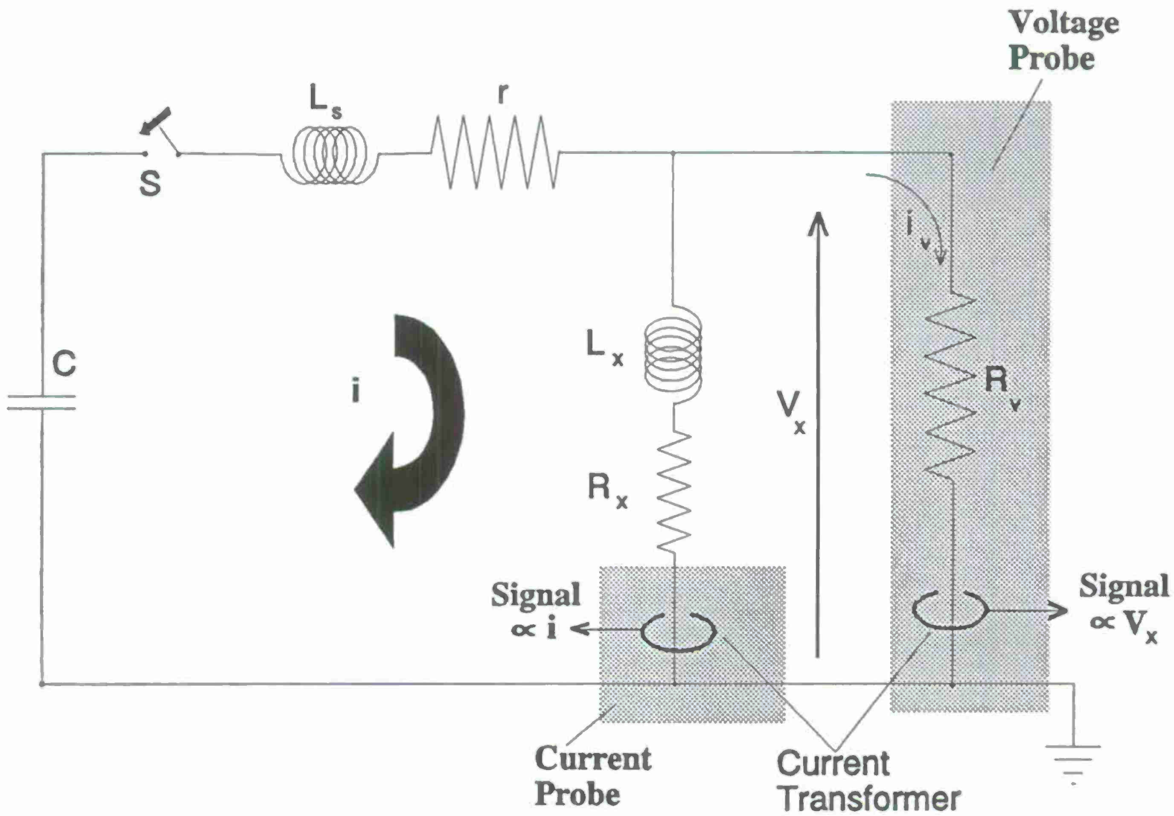

FIGURE 2-2. BASIC CONDUCTIVITY MEASUREMENT CIRCUIT

transformers to indirectly measure the current in a relatively large shunt resistor; see Figure 2-2. This current, i_v, is used to calculate the required voltage, V_x, where $V_x = i_v R_v$. The resistor, R_v, used here ranged from 100 Ω to 10 kΩ, and was made from a solution of copper sulphate ($CuSO_4$) in a polyethylene tube.

Conductivity in Detonating Explosives

Our work on the conductivity of explosives documents that the conduction zone of the explosive has a finite width.[14] The unreacted explosive acts as a good insulator with a breakdown strength of circa 20 kV/mm, but when it is detonated the reaction zone has a conductivity of the order of 200 mhos/m. The detonated explosive thus initiates current flow between the electrodes, and the subsequent electrical current and voltage are monitored as a function of time. By plotting voltage, V, as a function of current, I, i.e., a V-I plot, the dynamic nature of the conduction process can be determined.

For the particular arrangement shown in Figure 2-1, current flow in the Kapton is limited to the region adjacent to the conduction zone in the explosive. Current enters from the right, passes along the copper foil, down through the conduction zone of the detonating explosive and shocked Kapton, then back to the right, along the brass electrode.

The resistance R_x of the explosive and Kapton is then obtained from the slope of the V-I plot. In these experiments, we cannot directly measure the conductivity, $\sigma(x)$, but rather the integral of $\sigma(x)$ along the conduction zone. The methods used to measure $\sigma(x)$ directly are given in Reference 14. However, we can define a conductivity-zone width product, $\sigma\Delta$, where Δ is the effective conduction zone width, as follows:

$$\sigma\Delta = \int_0^\infty \sigma(x).dx \tag{2-7}$$

The $\sigma\Delta$ product is then related to the resistance, R_x, for this planar geometry by

$$\sigma\Delta = \frac{h}{WR_x} \tag{2-8}$$

where h is the total explosive and Kapton thickness and W, the electrode width.

In the transverse experiment, described here, the first resistance to be measured was that of the explosive alone. In the second half of the experiment the resistance of the combination of the Kapton and explosive was measured; see Figure 2-1. From these measurements both the explosive resistance and the Kapton resistance were obtained. Two explosives were used in this series of experiments: Detasheet type C-3* and PBX-9501.** Various types of Kapton were used; the details are shown in Table 2-1.

Results of Transverse Experiments

Typical current and voltage traces are shown in Figure 2-3 (shot KAP-89.02). In this experiment the first period (0 to 11 μs) of electrical conduction was through the Detasheet C-3 alone; in the second period (11 to 22 μs) the conduction was through the Detasheet and a 125 μm thick sheet of Kapton type H without adhesive.

At time $t = 0$ the detonation wave entered the electrodes and current began to flow. Because of the inductance of the circuit, the current could not rise instantaneously and the load voltage V_x fell to near 0 at about 250 ns. In the first 11 μs period, the current increased, as dictated by Equations (2-5) and (2-6). At the beginning of the second period the additional resistance of the Kapton was encountered. Consequently, the current fell and the voltage rose, as shown in Figure 2-4. From the V-I plots for the two periods the resistances were obtained.

Table 2-1 summarizes the details and results of eight experiments. In the table "x" denotes the total thickness of the Kapton layers. In shot KAP-89.01 two layers of Kapton adhesive tape were used, each layer comprised of 25 μm of Kapton film and 37.5 μm of adhesive. In shot KAP-89.02 the same thickness of material was used, but it was made of one layer of 125 μm thick Kapton with no adhesive.

Conclusions from Transverse Experiments

From the eight experiments the following conclusions can be drawn:

- Adhesives. Any type of adhesive backing of Kapton tapes significantly increased the resistance of the material and should therefore, be avoided.

- Thickness Effect. The conductivity of bare Kapton type H was dependent on the thickness in this application. For example, the resistance of one 125 μm layer was $\approx$300 mΩ whereas it was $\approx$4 mΩ for one 25 μm layer. Consequently, thick layers should be avoided.

- Multiple Layers. The resistance of two layers, side by side, was significantly greater than two layers on each side of the explosive, because of the thickness effect. Consequently, if the insulating properties of two layers of Kapton are

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*Manufactured by DuPont.
**PBX-9501: 95% HMX, 2.5% Estane, 2.5% BDNPA-F by weight.

TABLE 2-1. SUMMARY OF TRANSVERSE WAVE EXPERIMENTS

Shot KAP-	HE*	x μm	Kapton type**	Measured resistances, comments
89.01	C-3	125	2 layers, K250 (each 62.6 μm thick)	Kapton R_x = 294 mΩ with adhesive (explosive: 29 mΩ)
89.02	C-3	125	1 layer, bare	Kapton R_x = 300 mΩ
89.03	C-3	25	1 layer, bare	Kapton R_x = 4 mΩ
89.04	C-3	75	1 layer 75 μm,† 3 layers of 25 μm,†† bare	R_x = 100 mΩ and 60 mΩ respectively
89.05	C-3	125	2 layers, K250	Layers together and on opposite sides of explosive,†,†† R_x = 680 mΩ and 160 mΩ, respectively
89.06	C-3	50	2 layers, bare	Ditto,†,†† R_x = 60 mΩ and 30 mΩ, respectively
89.07	C-3	50	2 layers, K102	Ditto,†,†† R_x = 710 mΩ and 390 mΩ, respectively
89.08	9501	50	2 layers, bare	Layers on opposite sides of explosive, R_x = 5 mΩ

* High explosives (HE) used: Detasheet type C-3 and PBX-9501.

** Kapton type: K102 and K250 both have a 25 μm thick Kapton type H insulating layer with a 37.5 μm adhesive backing; K250 uses a silicone adhesive, K102 uses an acrylic adhesive. "Bare" refers to Kapton type H without adhesive.

† Where two types of tape were used they each occupied half the run length of the experiment.

†† The layers were divided in two on either side of the explosive, i.e., one layer on one side of the explosive, and one or two layers on the other side.

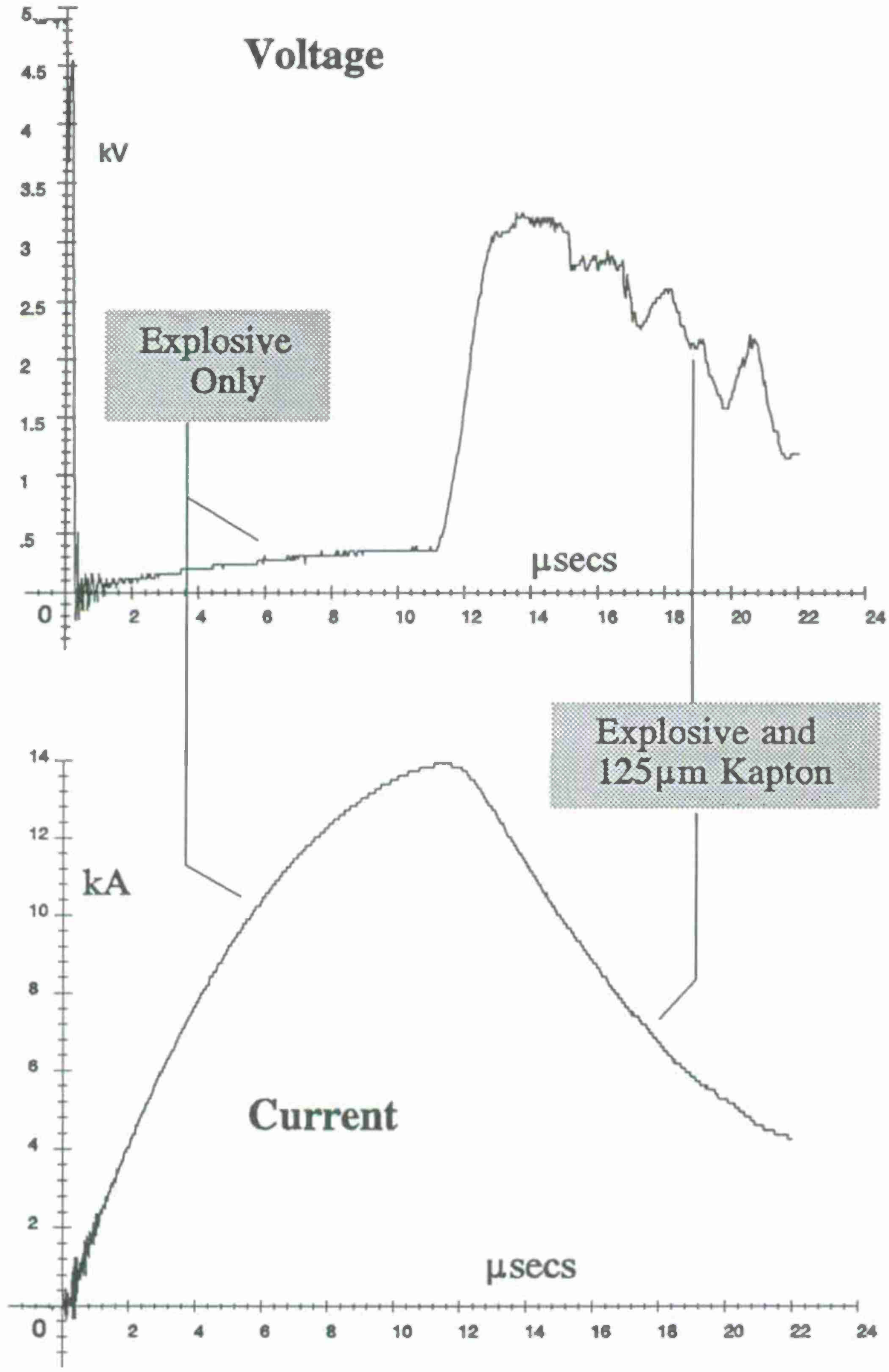


FIGURE 2-3. VOLTAGE AND CURRENT WAVEFORMS FOR DETASHEET C-3 AND 125 μm THICK BARE KAPTON, SHOT KAP-89.02

required, it is better to place them on each side of the explosive rather than next to each other. By placing them on each side of the explosive the resistance of the insulation during detonation will be relatively small.

Dependance of Conductivity in Kapton with Thickness for the Transverse Mode, the Thickness Effect

The apparent variation of the conductivity with thickness, for the transverse mode of conduction, is believed to be due to the finite conduction zone width in the explosive. Figure 2-4 shows an idealized explosive experiment in which a layer of Kapton is sandwiched between an electrode and the explosive, and a second electrode completes the circuit. The detonation passes from left to right in the explosive. The explosive's conduction zone trails behind the detonation front as shown. The effective duration of the zone, t_c, is of the order of 100 ns for PBX-9501.[14] The actual shape of the conduction zone can be described by a sharp rise of conductivity, σ, at the shock front, followed by an exponential decay with time or distance, as shown in Figure 2-4.

When the detonation front arrives at a point along the Kapton/explosive interface a shock wave is propagated into the Kapton as shown. The region to the left of the shock front (lightly shaded in Figure 2-4) is shocked into its conducting state. For clarity, Figure 2-4 does not show the shock reflected at the interface between the top electrode and Kapton, or any other of the multiple reflections that occur behind the shock front. Now it takes a finite time, τ, for the shock to traverse the Kapton film, i.e., $\tau = h/U_s$, where h is the Kapton thickness, and U_s is the shock velocity in the Kapton. If τ is greater than t_c, then conduction is greatly diminished because the explosive has ceased to conduct before the full thickness of Kapton has started to conduct. Current can still flow along the thickness of the shocked Kapton up towards the detonation front; however, the resistance of this path is large because the Kapton's conductivity is strongly pressure dependent,[5] and thus, diminishes rapidly behind the front. For instance, if the Kapton's resistance is R_K then

$$R_K = \frac{\left(\frac{h}{U_s}\right)D}{W\sigma_K h} = \frac{D}{U_s W \sigma_K} \qquad \text{(2-9)}$$

where W is the electrode width; D is the detonation velocity; σ_K, τD or hD/U_s, and h are the Kapton's conductivity, conduction path length and thickness. Assume for now that the Kapton is incompressible, i.e., h is not reduced by the arrival of the detonation shock. Typically, $D/U_s \approx 2$, so, it is σ_K that controls R_K. Now σ_K is a strong function of pressure. As the pressure falls behind the shock front, due to the structure of the detonation wave and the arrival of rarefactions, σ_K is likely to fall rapidly, and therefore R_K increases rapidly. Moreover, h is reduced because the Kapton is compressed by the shock, and this further increases the resistance.

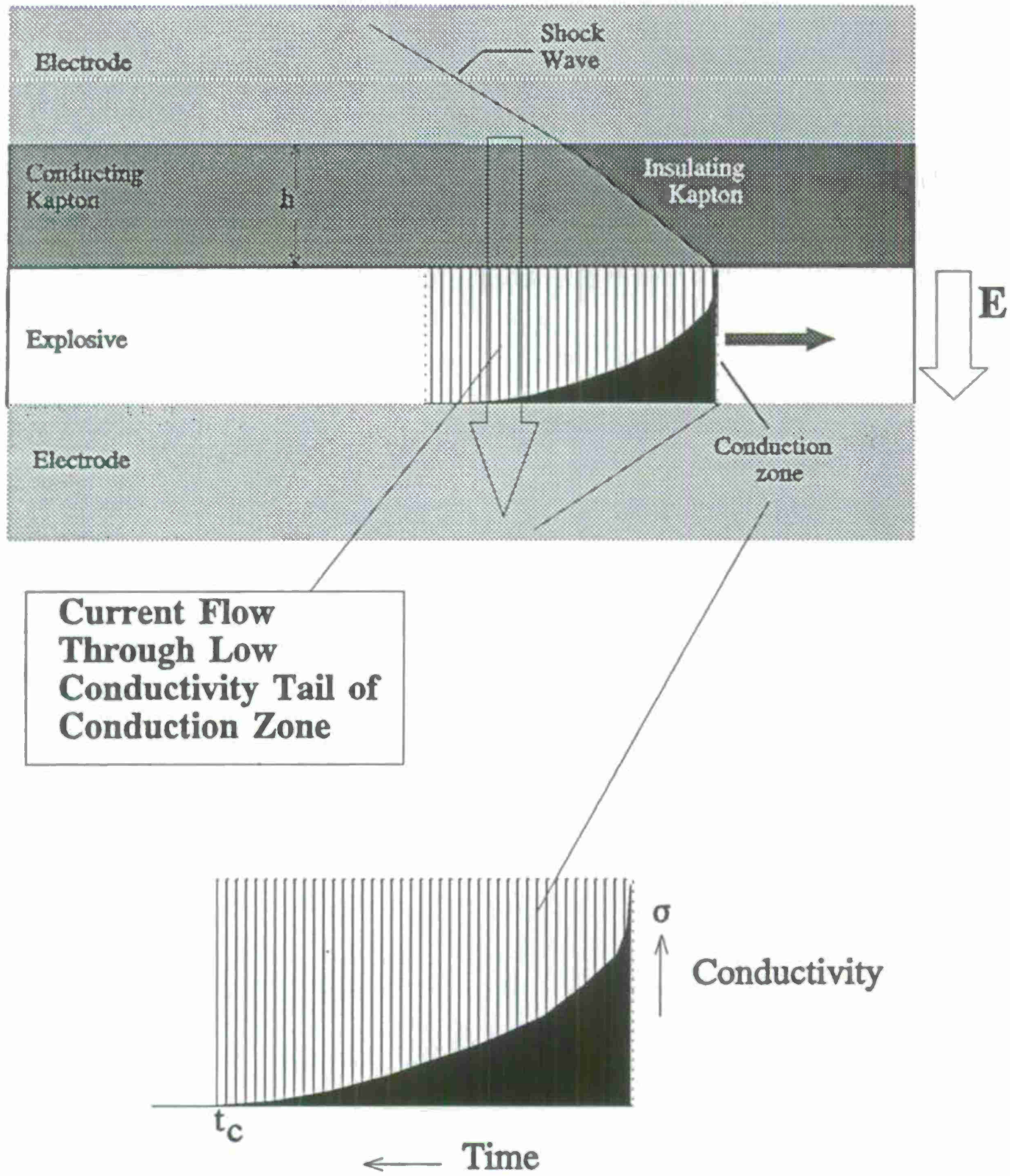


FIGURE 2-4. ELECTRICAL CONDUCTION IN SHOCKED KAPTON

The overall resistance of the circuit will always be increased by the Kapton. This is because the time delay in the Kapton, i.e, the time taken for the full thickness to be shocked into conduction, will always divert current flow away from the detonation front where the explosive's conductivity is a maximum. Consequently, the variability of the conductivity with Kapton thickness in the transverse mode is a function of the exponential decay of explosive and Kapton conductivities behind the detonation front. The time taken for the Kapton to be shocked into conduction is demonstrated in the next section.

Possible Penetration Effects

An alternative explanation for the thickness effect might have been that films of Kapton undergo mechanical failure under the action of the shock wave, so that the insulation is torn or penetrated by the electrode. Then thicker sheets would take longer to penetrate and would exhibit a larger resistance. However, the results of the conduction timing experiments, described next, demonstrate that conduction in the Kapton is due to shocked induced conductivity and not penetration.

CONDUCTION TIMING EXPERIMENTS IN KAPTON

The conduction timing experiments were designed to test the hypothesis that conduction in Kapton is shock-induced, and not due to mechanical failure.

The signals from each pin were connected to transient digitizers, operating at a sampling rate of 200 MHz, and a 1 GHz bandwidth analog oscilloscope with a risetime of 0.3 ns. All cables were carefully matched in electronic length to within 0.2 ns, using a time domain reflectometer. The risetime of the signal output in the ionization circuit can be obtained from Equation (2-4). Using values of 50 Ω for the load, 1 nF for the capacitor, and approximately 1 nH for the circuit inductance the zero to 90 percent risetime of the circuit was approximately 0.05 ns.

Ionization Pin Assembly

Four ionization pins were placed in a 25.4 mm diameter brass cylindrical holder as shown in Figure 2-5. The ionization pins had an outside diameter of nominally 0.8 mm, and were set on a circle of radius 3.175 mm; their inner conductors were insulated from the outer conductors with Teflon. Pins 2 and 4 were mounted flush with the front face of the brass holder and pins 1 and 3 were offset by the thickness of Kapton type H insulation. Pin 1 was offset by a 25 μm film, and pin 3 a 50 μm film. Both pins 1 and 3 were fitted into 3.175 mm brass plugs, as shown, which were the same diameter as the Kapton insulation which was added later.

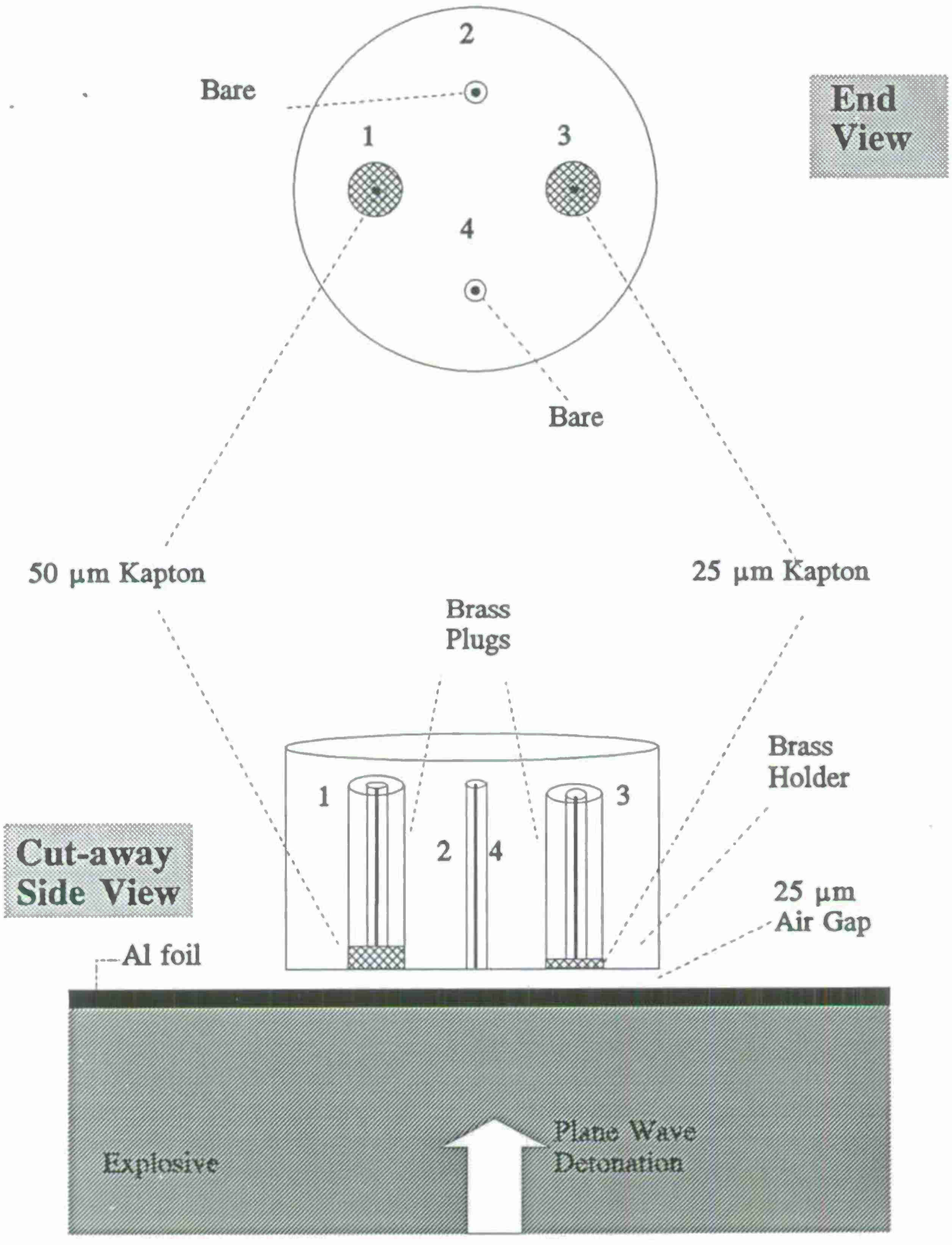


FIGURE 2-5. PLANE WAVE IONIZATION PIN EXPERIMENT TO DETECT ONSET OF CONDUCTION

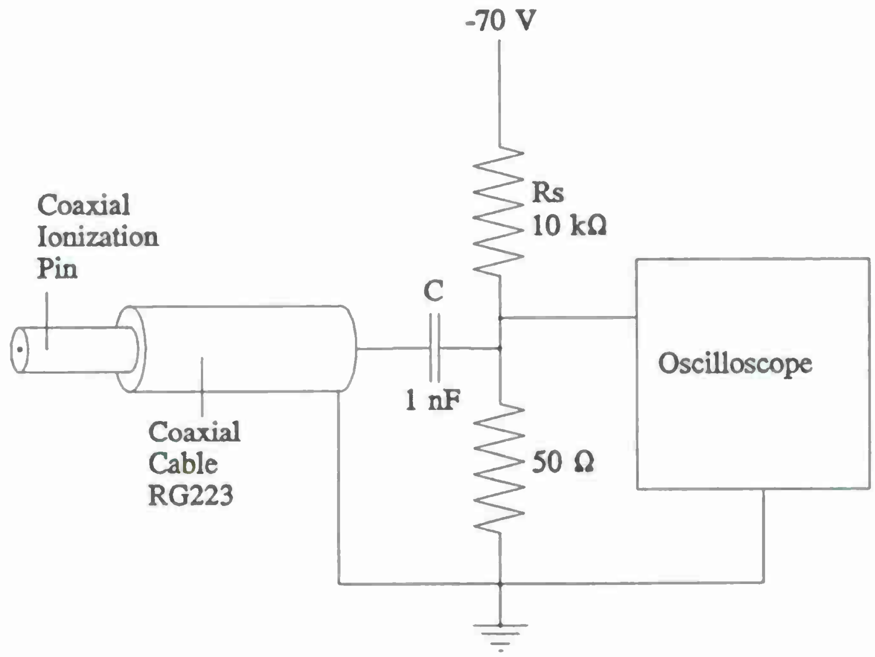


FIGURE 2-6. IONIZATION PIN CIRCUIT

The complete brass holder, with the pins and plugs in place but no Kapton, was placed in a 75 mm diameter aluminum plate to facilitate lapping. The complete assembly was carefully lapped and polished flat, then the 3.175 mm diameter brass plugs, for pins 1 and 3, were withdrawn to accept the Kapton insulators. Then the assembly was placed on a precision flat plate, the brass plugs were pushed down inside the brass holder against the plate, and the plugs were glued in place with epoxy.

Experimental Assembly

A 25 μm thick spacer (not shown) separated the face of the brass cylinder from an aluminum flyer. A 12.5 μm thick aluminum flyer was attached with a thin smear of silicone grease to a plane-wave explosive driver assembly. The flyer was projected by the detonation against the brass holder. The aluminum had a higher shock impedance than the explosive, therefore, it did not spall-away, i.e., separate from the explosive. Thus, a plane shock wave was launched into the four pins almost simultaneously. Pins 2 and 4 were immediately short-circuited by the aluminum foil. Pins 1 and 3 could only conduct after the shock waves had traversed the two Kapton layers; at that stage the conduction could be induced by penetration or by shock-induced conduction. The circuit is shown in Figure 2-6.

Results and Conclusions of the Conduction Timing Experiments

The experiment was performed several times to verify the repeatability of the data. The digitizer records for one experiment are shown in Figure 2-7. It was found that the tilt of the plane wave generator system produced timing differences comparable to the switching times, i.e., up to 10 ns. Consequently, the times when the pins started to conduct were misleading, i.e., the delays caused by wave transits in the Kapton were not always evident.

The structure of the records are consistent with an approximate shock wave speed in the Kapton of 2.5 $\pm$ 0.5 μm/ns, i.e., 2.5 km/s. It can be seen that both Kapton signals showed signs of ringing-up as the shocks reverberated between the higher impedance aluminum foil and ionization pin. This is consistent with a shock-induced conduction model because the conductivity is known to increase with pressure.[5]

The aluminum foil also rang-up as the shock pressures equalized between the pins and the explosive. The transit time of the shock across the aluminum foil and back is estimated to have been $\approx$3.5 ns. The rippling we observed on the analog oscilloscope records may have been due to this effect; the transient digitizers did not have the time resolution to detect such high frequency signals.

From these data, the conduction appears to have been due to shock-induced conduction in the Kapton and not by shorting of the pins due to penetration through the Kapton. If conduction was due to penetration of the Kapton then there would not have

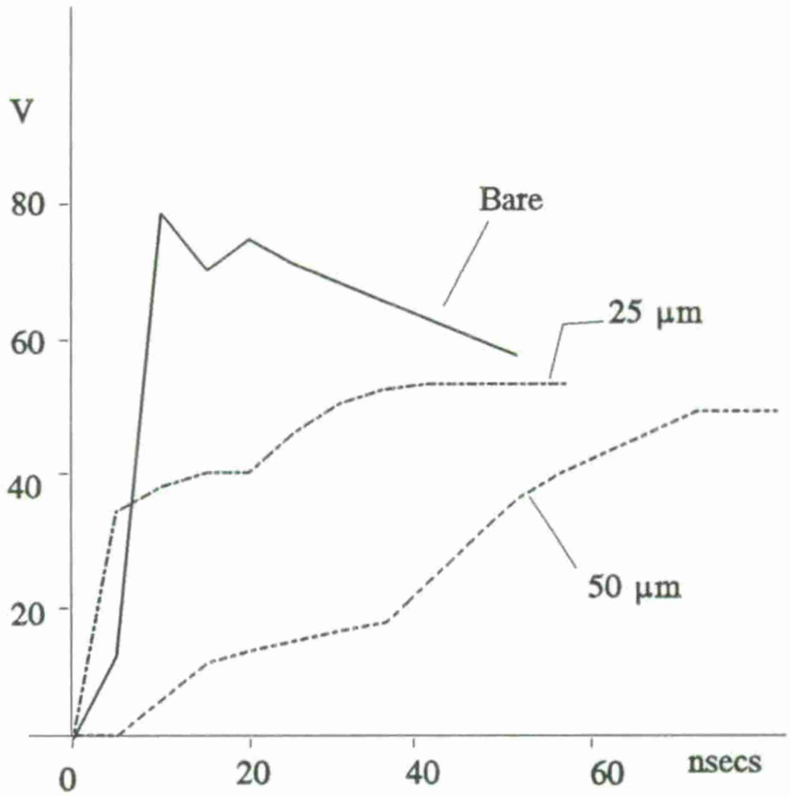


FIGURE 2-7. SIGNALS FROM THREE IONIZATION PINS: ONE BARE, ONE WITH 25 μm, AND ONE WITH 50 μm KAPTON

been a multi-stepped rise of voltage, instead the voltage would have risen to a plateau in one jump. Note that the conduction could not have been due to shock-induced conduction in the Teflon, that insulated the ionization pin, because Teflon is known to have a very low shock-induced conductivity.[5]

CHAPTER 3

DESIGN PRINCIPLES FOR KAPTON CLOSING SWITCHES

The switch designs described here are generic rather than specific. We have found that the closing switch, that relies on shock induced conduction in Kapton, can be successfully applied in many different ways provided that certain design principles are followed. The general principles of switch design are described together with examples of various switch applications.

In the transverse wave technique described here a shock wave is propagated perpendicular (transverse) to the direction of the electric field as was shown in Figure 1-1(B). The shock wave is generated by detonating sheets of explosive adjacent to the electrodes and insulation. With this technique, electrical conduction is maintained in the switch for at least as long as the detonation wave can be sustained. The time duration is only limited by the lengths of the electrodes and explosive sheets. For example, an explosive/electrode assembly 50 cm long would conduct for $\approx 70\ \mu s$ if the explosive's detonation velocity were ≈ 7 km/s. This allows very large electrical currents to be conducted, e.g., $>10^5$ Amps. These large currents are possible because of the long conduction times. The ultimate current is clearly limited by the rate of increase of current, di/dt, and the time for conduction so that

$$i(t) = \int_0^t \frac{di}{dt} dt \tag{3-1}$$

and from Equation (2-3) it can be shown that the maximum di/dt occurs when i = 0 and t = 0 when

$$\left(\frac{di}{dt}\right)_{max} = \frac{V_c}{L} \tag{3-2}$$

In other words, di/dt is limited by the inductance of the circuit so, conduction must continue in the switch for a relatively long time for large currents to be obtained.

The switch closes very rapidly, i.e., in a time equal to the transit time of the shock wave. For example, a 25 μm thick Kapton film will become fully conducting in less than ≈ 10 ns; this was discussed in Chapter 2. During this transition the switch is resistive and large energies could be lost if the transition time was long. The rapid closure minimizes the energy lost when the switch transitions between its open and closed condition. Moreover, the switch relies only on the explosive energy for its successful closure; this makes the switch electrically energy-efficient. For example, electric energies of only a few millijoules have been successfully switched within nanoseconds, with negligible loss, using the technique.

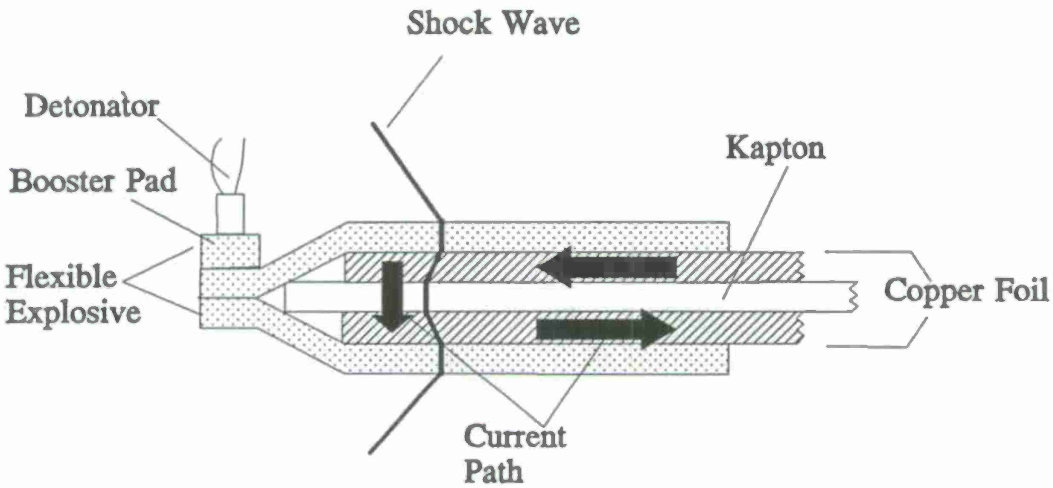
CONFIGURATIONS

The typical explosively-driven Kapton closing switch forms a parallel electrode stripline. This is made of two thin metal electrodes, typically made of brass, copper, or aluminum; a thin insulating layer of Kapton between the electrodes; one or more layers of sheet explosive (typically Dupont Detasheet type C-6); an explosive booster pad; and a Reynolds RP80 detonator. See Figure 3-1(A).

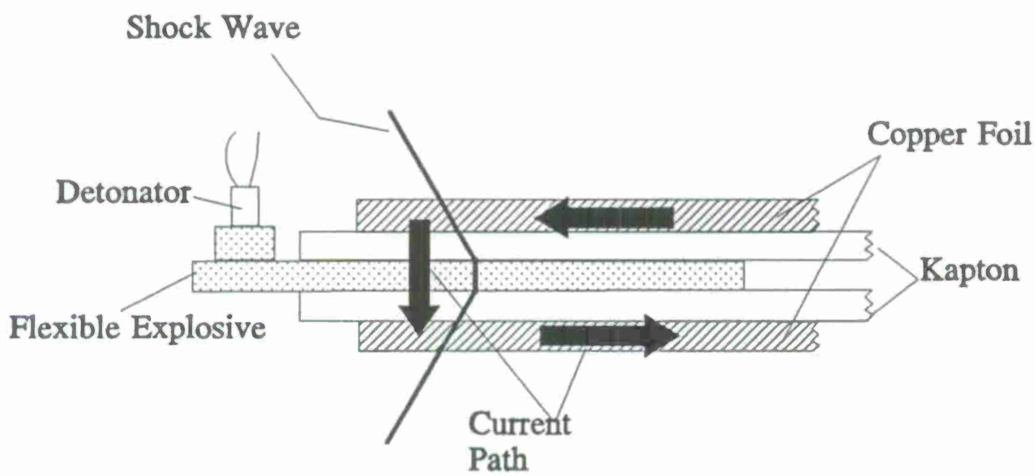
One end of the explosive sheet is detonated by the detonator and booster pad assembly. A detonation wave then sweeps down the length of the explosive sheet, beside the electrodes. Depending on the design, the detonation wave may propagate through the electrode and into the Kapton, or may propagate directly from the explosive into the Kapton. The first case is shown in Figure 3-1(A). The conducting Kapton behind the detonation front allows electrical current to pass from one electrode through the conducting Kapton, and back through the other electrode. In the second case, shown in Figure 3-1(B), current passes from the electrodes through both the two films of shocked Kapton and the conduction zone of the explosive.

IMPORTANCE OF THIN INSULATION

It was shown in Chapter 2 that thick layers of Kapton do not conduct well when shocked in the transverse mode because of geometry and pressure effects. Now electrical conduction in the explosive is limited to a relatively narrow region of the explosive, immediately behind the detonation front.[14] However, conduction across the full thickness of the Kapton cannot start until the shock from the detonation front has crossed it. If the shock transit time across the Kapton is greater than the duration of conduction in the explosive then the resistance of the circuit is greatly increased. This was shown in Figure 2-4 where conduction is limited by the width of the explosive's conduction zone for a design similar to that of Figure 3-1(B). By the same token, the duration of the shock wave in the Kapton limits conduction in thick insulators when designs typified by Figure 3-1(A) are used. So, it is important that the shock wave transit time across the Kapton is short compared to the conduction zone time. Otherwise, the times of peak electrical conduction in the adjacent layers of explosive and Kapton will not be synchronized and conduction will be impaired. Thin insulating Kapton sheets should be used, e.g., less than 75 μm thick, especially in the sandwiched designs described below.



(A) Explosive Shocks Kapton Through Copper.



(B) Explosive Forms Part of Conduction Path.

FIGURE 3-1. TYPICAL SWITCH ASSEMBLIES

Explosives

For convenience and ease of use Detasheet (type C-3 or C-6) explosive has been used in most of the work described here. It has a good electrical conductivity, is flexible, relatively safe to handle, easy to cut to size, and inexpensive. However, any explosive with a detonation pressure exceeding ≈ 9 GPa can be used. If the explosive forms part of the electrical circuit, explosives with good electrical conductivities during detonation must be used.[14] Sheets of PBX-9404 or PBX-9501 as thin as 1 mm have worked very well in these designs.

Electrodes

Any good electrical conductor can be used. Care must be taken to eliminate sharp corners and edges to prevent dielectric breakdown problems in the unshocked Kapton. The electrodes should be in a low inductance stripline configuration to minimize circuit losses.

Polymer

Any insulation material that exhibits a strong shock-induced electrical conductivity could be used. Kapton and Mylar are available in thin sheets and are good choices. The material chosen should also exhibit good insulating properties in its unshocked condition, i.e., prior to being shocked.

Sandwiched designs

For high voltage operation the insulation must be capable of withstanding the high applied electric fields. However, as was shown above, if the insulating sheet is too thick then it may not conduct when shocked. Sandwiched designs, therefore, have been developed to circumvent these problems. The maximum voltage that may be withstood by the insulation is the sum of the maximum voltages of the individual layers.

In the sandwiched design alternating layers of explosive and thin sheets of Kapton are used; see Figure 3-2. By alternating explosive layers with thin sheets of Kapton the shock waves are propagated from both sides of the Kapton and the transit times are kept short. The maximum voltage that can be withstood is the total of the voltages for each individual Kapton sheet (plus the insulation provided by the undetonated explosive).

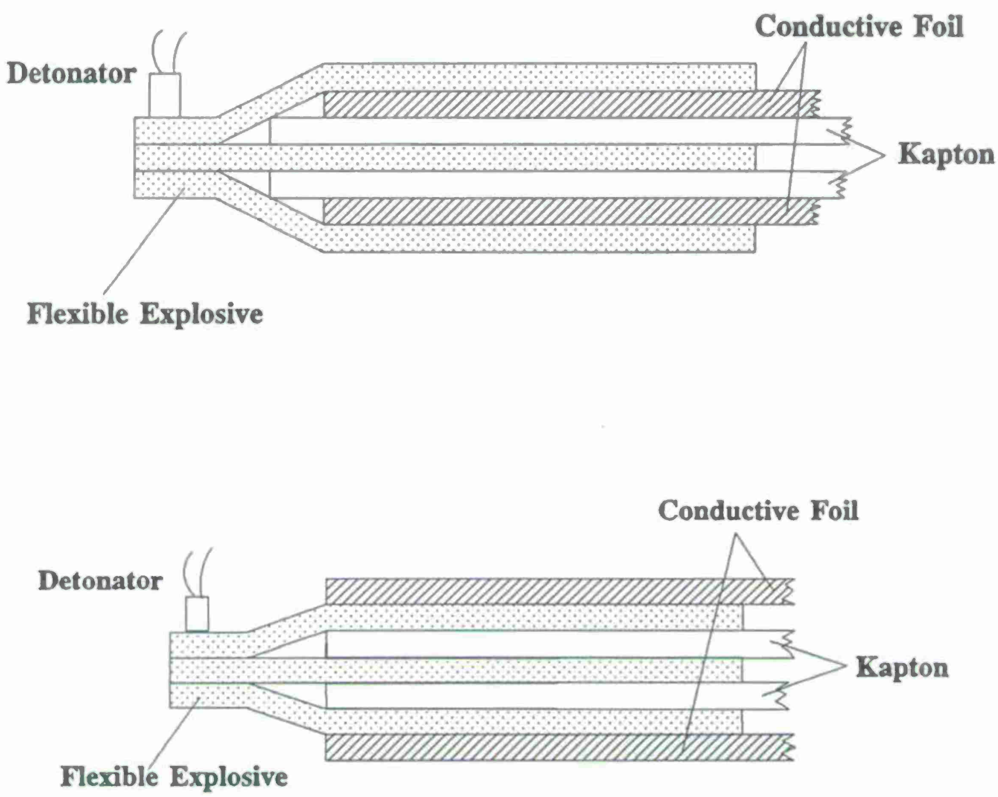


FIGURE 3-2. TWO SANDWICHED-SWITCH DESIGNS

Shock Generation

Any method of sweeping (transverse) wave generation may be employed. For example, a metal flyer plate may be impacted against the Kapton at an angle to generate a sweeping (transverse) shock wave. This must generate pressures in excess of 9 GPa and shock durations greater than the transit time in the Kapton, as described above.

CHAPTER 4

EXPERIMENTAL RESULTS OF SWITCH OPERATION

A wide range of experiments have been performed using the kinds of switch designs described in previous chapters. As evidence of the successful operation of these switches the results of using three of them are described.

TEST OF HIGH POWER OPERATION IN THE BASIC SWITCH

To test the operation of the switch, a simple experiment was performed. The basic switch design was similar to the one shown in Figure 3-1(A). The insulator was one sheet of 25 μm thick Kapton type H, sandwiched between two 25 μm aluminum foil electrodes. On the outsides of the electrodes two sheets of Detasheet type C-3 (3 mm thick) were used. The length of both of the aluminum electrodes between the explosive sheets was 25 mm; the total length of each of the Detasheet sheets was 50 mm, so that there was 25 mm of travel before the detonation wave entered the electrodes.

One end of the top explosive sheet was detonated by a Reynolds RP80 detonator; see Figure 3-1. The detonation wave was transmitted from the top to the bottom sheet, and then swept down the length of both sheets on the outside of the electrodes. (Note that plane or line wave generators are not necessary here.) The same 5 kV capacitor bank with current and voltage diagnostics, described in Chapter 2, was used.

Results

The results are shown in Figure 4-1 where the voltage across the switch and the current are shown. The capacitor bank was turned on at 0 μs, and the detonation wave entered the electrodes at 1 μs. At 1 μs the voltage fell from 5 kV and the current started to rise. The rate of increase of current was controlled by the inductance of the capacitor bank, 2 μH here. With the switch fully conducting, the voltage fell to less than 30 V and the current rose to 8 kA; this was equivalent to a switch resistance of less than 4 mΩ, which is consistent with the data of Table 2-1. The detonation velocity in Detasheet type C-3 is nominally 7 mm/μs. Consequently, the wave exited the electrodes after $\approx$3.5 μs; the switch started to turn off at that point as the explosive's conduction zone left the electrodes.

Note that the current can never turn off instantly because of the inductance in the circuit. The inductance causes a large voltage, i.e., Ldi/dt, to be added to the applied voltage. Hence the voltage rose rapidly at 5 μs as the inductance opposed the change of current i.

EEE EXPERIMENTS

As part of the EEE program,[1] a method was required to insulate the explosive PBX-9501 up to fields in excess of 20 kV/mm. However, this insulation had to have a negligible resistance when shocked by the detonating explosive. The Kapton insulation technique was developed to meet this need.

Experiment

The basic experiment is shown in Figure 4-2. In this experiment, a sheet of 6.35 mm thick PBX-9501 was detonated by a line wave generator system, not shown. The detonation was propagated from right to left between two 12.7 mm wide, 12.7 mm thick brass electrodes. The electrodes were insulated from the explosive by two layers of 25 μm thick Kapton type H insulation, one on each side of the explosive.

The electrodes were connected on the left hand end to a 1 MJ, 20 kV capacitor bank; the connections and capacitor bank do not appear in the figure. For this experiment the bank was charged to 9.5 kV. The current was measured with Rogowski coils and the voltage was measured with $CuSO_4$ resistors.

Results

The results of the experiment are shown in Figure 4-3 where the voltage between the electrodes and the current are shown. (These data appear unusually smooth because they were obtained with low bandwidth (1 MHz) oscilloscopes.) The capacitor bank was turned on at 0 μs, but no current flowed because the switch was in its 'off' state. At 1 μs the detonation wave entered the Kapton and electrodes, and current began to flow. At 14 μs the detonation wave exited the electrodes and the current began to turn off.

As shown in Figure 4-1, the current could not turn off instantly because of the inductance in the circuit, and the voltage rose rapidly after 14 μs as the inductance tried to maintain the current constant. The voltage was developed across the explosive between the Kapton layers, i.e., the voltage across the Kapton was negligible. The switch successfully controlled a power of approximately 250 MW.

Over 100 similar experiments have been fired, with thicknesses of PBX-9501 ranging from 1 to 25.4 mm, in which the switch technique has operated successfully.

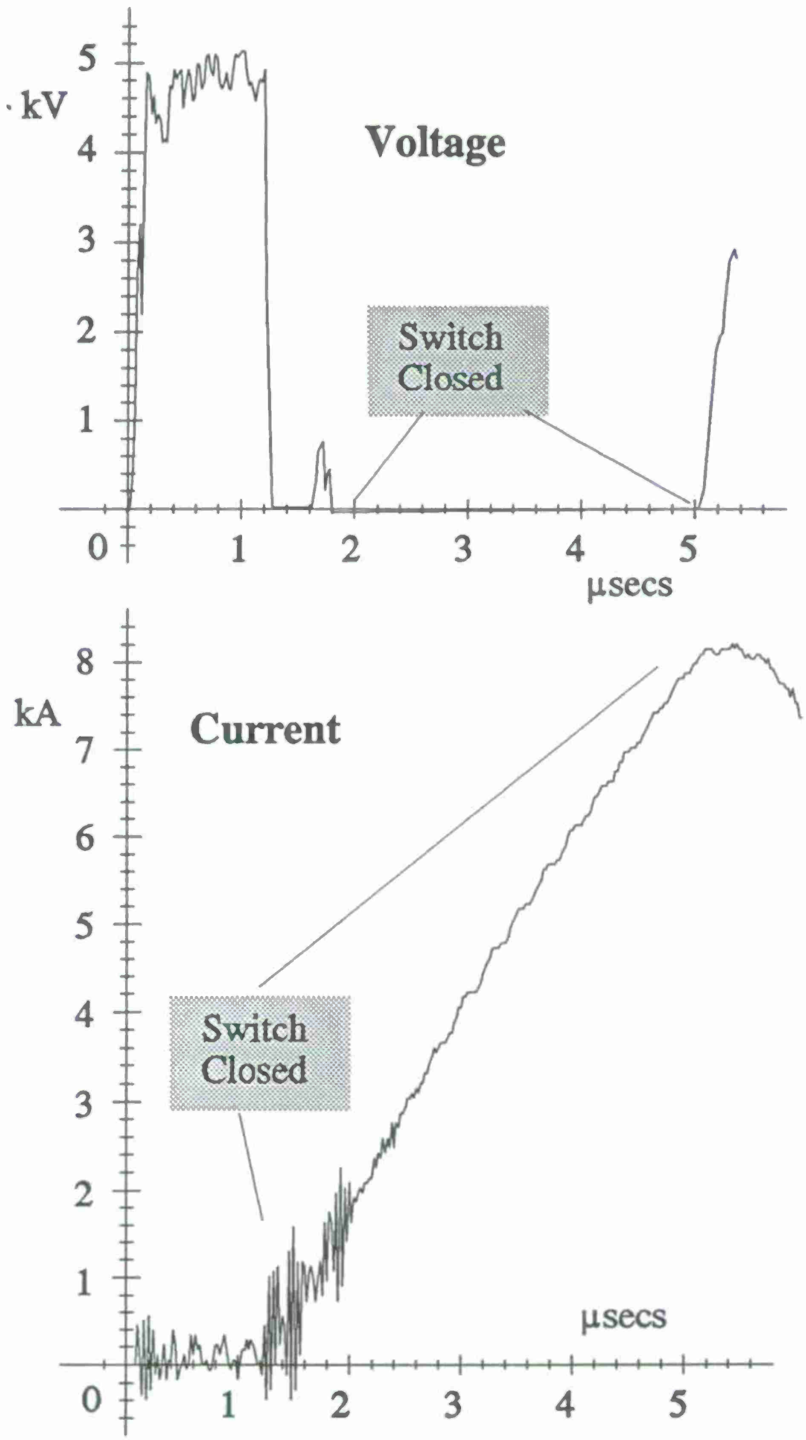


FIGURE 4-1. VOLTAGE AND CURRENT WAVEFORMS FOR SIMPLE, HIGH POWER KAPTON SWITCH

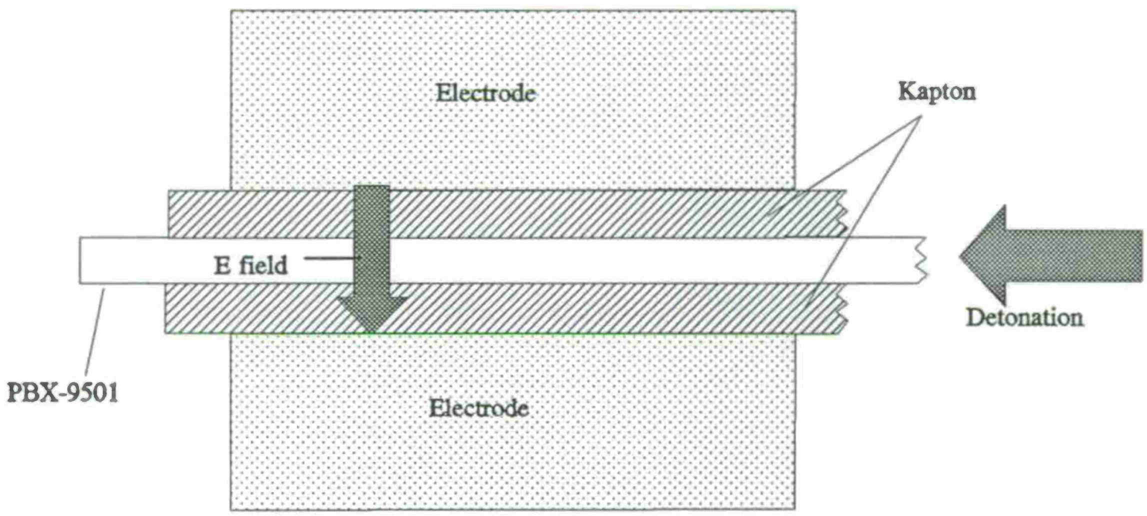


FIGURE 4-2. BASIC ELECTROMAGNETIC ENERGY ENHANCEMENT EXPERIMENT

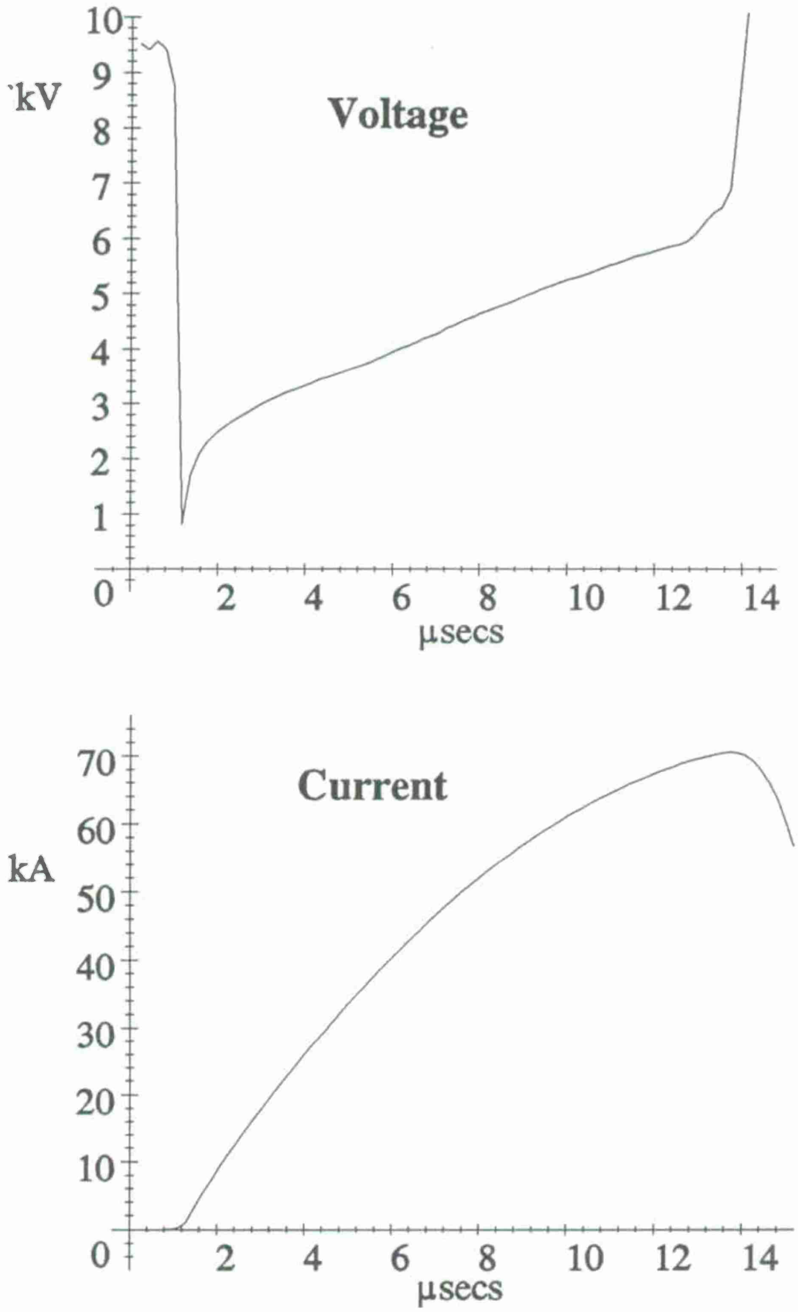


FIGURE 4-3. VOLTAGE AND CURRENT WAVEFORMS IN ELECTROMAGNETIC ENERGY ENHANCEMENT EXPERIMENT

TEST OF LOW ENERGY OPERATION IN THE EFFICIENT ENERGY TRANSFER EXPERIMENT

The Efficient Energy Transfer Experiment was designed to efficiently couple a prescribed quantity of electrical energy directly to an explosive under test, in this case PBXN-103. The test relied on the successful operation of an explosively-actuated Kapton switch to transfer very small electrical energies without significant loss. The complete details of the experiment are described elsewhere.[15] This was an experiment to study the sensitivity of the explosive to electrostatic discharge (ESD) ignition. The experimental conditions were designed to simulate the discharge of electrical energy into the explosive directly from an insulating case. In other words, the experiment was designed to provide a low inductance, low resistance path from the case to the explosive. The electrostatic charge on the case was closely controlled, and the discharge currents and voltages were measured.

In this experiment an energy of 580 mJ was directly coupled into the explosive sample. This energy, 580 mJ, represented a surface charge of $\approx 68\ \mu C/m^2$ on the insulating case. Conventional switches were not suitable for this application, because they turn on relatively slowly and thereby consume significant energies. However, the explosively-actuated switch uses the explosives energy to operate, and it turns on rapidly, i.e., within 10 ns. Hence the switch turns on with a negligible expenditure of electrical energy.

Experiment

The experimental arrangement is shown in Figure 4-4. The series inductance of the circuit was only 80 nH in this experiment. This low circuit inductance was required to transfer a high electrical power in the discharge. The manufactured storage capacitor was placed against the explosive and an efficient Kapton closing switch was employed. Hence, the energy dissipated in the circuit was negligible compared to the electrical energy deposited in the test sample.

Both voltage and rate of change of current, di/dt, data were recorded. The di/dt data were integrated to determine the current, i, which in turn was used to determine the electrical charge transferred to the sample.

Kapton Switch. The details of the switch are shown in Figure 4-4. Two strips of 12.7 mm wide by 125 μm thick copper foil were separated by 5 sheets of 25 μm thick Kapton type H. The Kapton sheets extended 75 mm beyond the edges of the copper foil on every side to avoid dielectric flash-over.

The switch was sandwiched between two sheets of flexible explosive, Dupont Detasheet C-3. The strips of Detasheet were 25 mm wide and 75 mm long, with 50 mm covering the electrodes and 25 mm extending beyond the electrodes. A 25 mm square

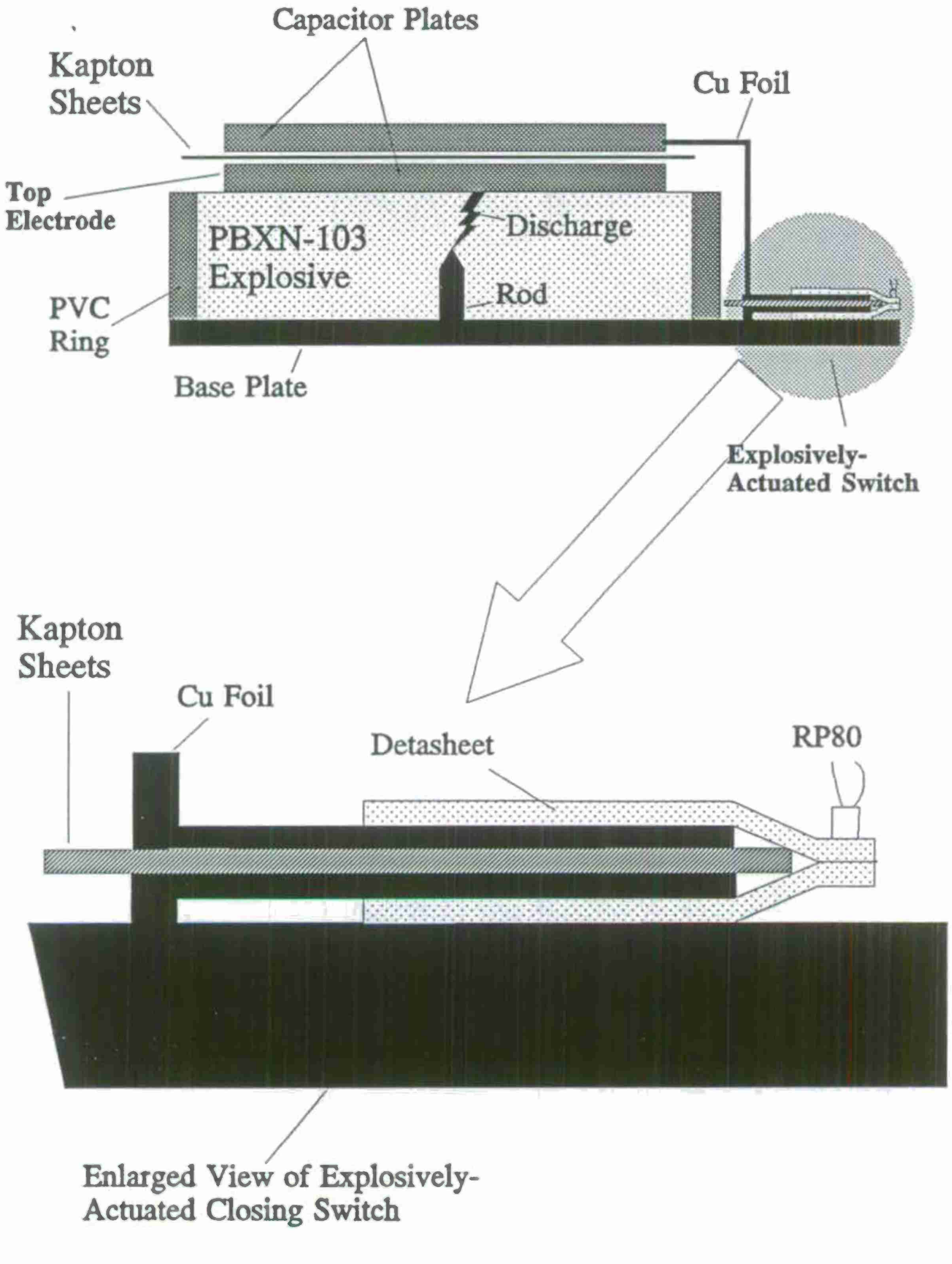


FIGURE 4-4. EFFICIENT ENERGY TRANSFER EXPERIMENT

section of Detasheet C-3 was used as a booster and placed over the section of Detasheet extending past the electrodes. Detonation was initiated in the Detasheet with a Reynolds Industries RP-80 exploding bridge wire detonator.

The Electrodes. A point-to-plane electrode arrangement was used to concentrate the discharge at the center of the sample. The low voltage electrode was a 3.175 mm diameter sharpened brass rod which was soldered to the base plate. The PBXN-103 explosive was cast around this electrode. The high voltage electrode was a 127 mm diameter brass disk which was placed against the exposed surface of the explosive. A 1.27 cm spacing was provided between the two electrodes.

The Test Sample. The Navy explosive PBXN-103 was used in these tests. The explosive sample was a 127 mm diameter by 19 mm thick disk. Each sample was made by casting the explosive into a 127 mm outside diameter polyvinylchloride (PVC) pipe section. A 9.53 mm thick brass plate was used as the base for each mold to facilitate connections to the low voltage electrode. After casting, the exposed surface of the explosive was machined flat to the desired sample thickness.

The Capacitor. A parallel plate capacitor was manufactured from two 127 mm diameter by 6.35 mm thick brass disks, these were separated by two sheets of 75 μm thick Kapton type H insulation. The capacitance was 1.3 nF, as measured on a Hewlett Packard HP 4277A LCZ bridge at frequencies from 10 kHz to 1 MHz. The high voltage plate of the capacitor also served as the high voltage electrode. The explosive sample was placed directly against the capacitor to provide a direct path from the capacitor to the sample.

The plates of the capacitor were connected across a DC power supply (not shown in Figure 4-4). The plate against the explosive was connected to the high voltage side of the power supply through a 25 kΩ resistance. This resistance served to limit current flow from the power supply during the time of discharge. The electrical energy stored on the capacitor was transferred to the sample via the closing switch.

Results

Two experiments were performed at 30 kV with stored energies close to 580 mJ. The switch proved to be very efficient. The electrical data showed that within the accuracy of the measurements, i.e., with an error of $\approx$1 percent, all of the stored energy was transferred to the sample.

CHAPTER 5

CONCLUSIONS

The designs and manufacture of several explosively-actuated electrical closing switches have been described. It has been shown that these switches can close within a few nanoseconds and can handle very large electrical powers. Moreover, they are energy efficient, with a low inductance, and a low resistance when closed; but are able to withstand high voltages when open. The switch technique exploits shock-induced conductivity effects in insulators, e.g., Kapton.

The key to the successful operation of these switches is to use them in the transverse mode of operation, i.e., where the detonation wave travels transverse to the applied electric field. The experiments documented in Chapter 2 identify parameters crucial to the successful operation of the switch, i.e., the effects of adhesive layers, insulating polymer thickness, and explosive electrical conductivity. Other experiments demonstrate that conduction in the shocked Kapton is caused by shock-induced conduction, not by mechanical tearing of the polymer.

The results of using the switch in various applications show that the explosively-actuated closing switch, using Kapton in the transverse mode, is effective, simple, efficient, and inexpensive.

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The designs and manufacture of several explosively-actuated, electrical closing switches are described. The switches are fast operating; can handle very high electrical power; are highly energy efficient, with low inductance and low resistance, when closed; but are able to withstand very high voltages when open. The switches exploit shock-induced conductivity effects in polypyromellitimide insulators (PPMI), e.g., Kapton. The key to the successful operation of the switches is to use them in the transverse mode of operation, i.e., where the detonation wave travels transverse to the applied electric field. Through the research described in this report, the many factors that are crucial to the design of an effective switch have been identified. Various switch designs and the results of using them in numerous applications are provided.

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